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Infrared Study of a Piston Ring Temperatures in a Fired Engine

Final Technical Report

by

Dr H A Spikes

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ABSTRACT

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LIST OF KEYWORDS

Engine
Diesel Engine
Piston
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Infrared
Infrared Emission

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1. INTRODUCTION

This is the final report on the project "Infrared Study of Piston Ring Temperatures in a Firing Engine", which has been conducted in the Tribology Section, Imperial College under the supervision of Dr H A Spikes. The study has been supported by a one year research contract from the United States Department of the Army.

The program concerned the insertion of sapphire windows in a single cylinder Petter diesel engine and the measurement, through these windows by means of infrared emission, of temperatures reached on the faces of piston rings and lands during a firing cycle.

This report describes the background to the work, the experimental method, results and a discussion. It concludes by considering the extent to which the original objectives have been met.

2. BACKGROUND

The piston ring/liner contact has long been recognised as an area that imposes performance and design limitations upon reciprocating engines. Problems that result from unsatisfactory lubrication of this contact include bore-polishing, piston ring scuffing and excessive liner wear.

In general, most problems occur at or near top dead centre where low piston velocity means that hydrodynamic film thickness is low and also where the temperature is highest, due to the proximity of the combustion chamber. These two factors, oil film thickness and temperature are interrelated, since high temperature reduces the viscosity of the lubricant, resulting in low oil film thickness as well as causing thermal distortion, whilst low oil film thickness may cause higher local friction and thence more heat generation.

There are a number of reasons why it is of considerable practical importance to be able to measure, with reasonable accuracy, the temperature of the piston ring and liner surfaces:

(i) Such values cannot yet be reliably predicted from computational models and are, indeed, needed to assist in the development and

validation of such models.

(ii) These values are needed to explain performance problems that arise in existing engines, especially with respect to scuffing.

(iii) These values are required in order to understand the influence of lubricants and engine design upon piston lubrication and thence to optimise these factors.

(iv) In recent years there has been a steady trend towards higher and higher engine temperatures and to lower viscosity lubricants. In the next decade we are likely to see this trend accelerate with the development of very high temperature, advanced engines. When moving into such uncharted technological fields it is of particular importance to be able to measure directly key, performance-controlling parameters.

Whereas the piston ring/liner temperature is probably most critical in determining lubricant film formation, of equal importance in practical terms is the temperature of the top land. This is generally hotter than the rings and it is here that the lubricant is most stressed with respect to its thermal and oxidative stability. The response of the lubricant to these conditions determines the extent of deposit formation and, indirectly, wear and bore polishing. It is thus important to know the temperatures reached by the top piston land surface in order to be able to design and realistically test lubricants.

Up till the present, the principle means of measuring piston temperatures has been to embed thermocouples close to or at the surface of the piston or liner. Wing and Saunders (1) give a detailed description of such devices and of their use in measuring piston groove temperatures, and similar work has been carried out by a number of authors (2)(3). Other techniques employed to measure piston temperatures include fusible or otherwise temperature-sensitive plugs, hardness recovery techniques (4)(5) and, recently, a "crystalline temperature meter" (6).

Most of these methods have two major limitations. Firstly they generally measure the temperature of the bulk liner or piston rather than that of the piston ring. Piston rings must be free to rotate and thus it is difficult to arrange for thermocouple leads to reach them in firing engines. Furuhama

and Suzuki have succeeded in using long lead thermocouples to measure piston ring temperatures, but only at 50 μm below the piston ring face surface (3). From the point of view of understanding tribological responses such as piston ring scuffing it is crucial to know the temperature of the piston ring surface itself. Most workers assume that this is similar to the temperature of the bulk piston ring. However simple application of flash temperature theory (7) to the problem, using typical engine conditions, suggests that a significant flash temperature rise may occur due to sliding, resulting in piston ring face temperatures being higher than those of the bulk ring. Such flash temperatures decay within a few microns and are thus not satisfactorily measured with embedded thermocouples.

The second limitation of thermocouples and similar devices is their low response time, which makes it difficult to study transient temperature variations. If we assume an engine speed of 1000 rev/min and wish to record a transient temperature variation lasting 10 degrees of crank angle, the time constant of the measuring device must be approximately 2ms. This is an order of magnitude less than the response time of small, bead thermocouples (1).

Thus there is a dearth of direct information about the actual temperatures reached by piston ring faces and land surfaces in operating engines.

One method of directly acquiring information about piston ring conditions involves observation through a hole in the cylinder wall. This approach was pioneered by Pywell and Pike (8) who used it to observe piston ring scuffing. The method was further developed in the authors' laboratory to study the influence of engine lubricant composition on piston ring scuffing (9). The hole permitted the onset of scuffing on the rings to be recorded using a stroboscopically illuminated video recorder. An infrared microscope was also used in this study to observe the temperature rise produced on the piston ring during scuffing (9) (10).

In recent work the approach has been extended at MIT by inserting a quartz window in a fired diesel engine and using laser fluorescence to successfully measure oil film thickness during steady operation (11) (12).

3. EXPERIMENTAL APPROACH

The basis of the current study has been to insert 5 mm diameter sapphire windows in the liner of a diesel engine at various positions. Sapphire is transparent both to visible light and to thermal infrared radiation. It is thus possible to both view the piston and also to monitor its surface temperature using an infrared (IR) thermal microscope. This method of measuring temperature has two advantages Firstly true surface temperatures rather than bulk temperatures are measured. Secondly the response time of IR detectors is very fast. In the current work the extent of infrared emission was measured every 20 μs, permitting observation of the temperatures of rapidly moving surfaces.

A single cylinder Petter AV1 diesel engine was employed in this study. Three window holders were made from chilled cast iron and inserted in the cylinder wall at positions corresponding to the centre of the top compression ring at top dead centre, mid stroke and bottom dead centre respectively. The ring pack of the engine employed has three compression and two scraper rings.

Each window holder was sealed against the outer liner wall with a copper seal and compression of this seal using a screw thread enabled accurate control of the spacing between cylinder liner surface and window surface. In the first half of this study the windows used were set back from the cylinder liner by 0.10 to 0.25mm. At a later stage the sapphire was fitted slightly proud of the liner and then diamond-honed to form a curved surface flush with the liner wall. A diagram of the window holder design is shown in figure 1.

The overall experimental and optical setup is shown schematically in figure 2. The engine is operated under a fixed load at a set jacket coolant temperature. Infrared emission is monitored by the IR microscope operating in either transient or chopped mode and the IR signal is fed into a high speed storage oscilloscope. A magnetic plug and detector inserted in the flywheel produces an electrical pulse at each top dead centre position (TDC) of the piston. This pulse is used in two ways. Firstly it is fed into one channel of the oscilloscope to provide a piston position reference. It is also passed through a simple electrical circuit which supresses every second pulse and allows the remaining pulses to be delayed by a fixed time interval.

Halving the number of pulses means that there is just one for every full cycle of the four stroke engine. Consequently this pulse train may be used to trigger and accumulate, in the oscilloscope, IR emission readings starting at any chosen portion of the firing cycle over a sequence of engine cycles. This averaging process greatly improved the signal to noise ratio of the system.

4. DETAILS OF IR METHOD

Temperature measurements were carried out using an infrared emission microscope with a 1/2x objective. In the first part of the work a Barnes RM2a model was employed. However this operates in a transient AC mode making calibration difficult as will be described later in this report. To overcome this problem, later stages of the study used a custom-built microscope similar to the Barnes except that the signal was collected and amplified in DC mode. Both microscopes were focussed through a sapphire window in the liner by removing the piston from the engine and placing a small lamp as an IR source inside the engine next to the window. A gold mirror was used to direct the infrared signal from the piston ring/liner contact to the upright microscope. The IR measurement area depends upon the optics employed and in this study was 800 μm^2.

With the window set back from the liner surface there is a likelihood of oil being trapped between ring and window. There may also be a significant quantity of oil between piston lands and liner. This could have two effects on the measured infrared emission. Firstly there might be emission, not just from the piston ring metal surface but also from this trapped oil. Secondly there is a possibility that the oil film will absorb radiation emitted from the ring surface. In an attempt to limit the effect of emission from the oil, an infrared filter was introduced between engine and IR microscope. This filter was chosen to selectively remove the infrared radiation in the frequency range emitted by hydrocarbon-based oils whilst still transmitting most of the lower frequency radiation emitted by hot metal surfaces. The filter absorption characteristics are shown in figure 3.

For a flush-mounted window the thickness of oil between window and ring is too small to contribute significantly to the measured emission but the filter was still retained for these measurements.

5. INTERPRETATION OF RESULTS

In interpreting the results it is important to be aware of just what portion of the piston surface is being observed by the microscope at any given time. This is not straightforward since the piston is reciprocating and is thus moving at varying speed past the window.

To facilitate interpretation of results, sketches of the view of the piston as it passes each window have been prepared and are shown in figure 4. These, in effect, transform the piston from being linear with respect to actual size to being linear with respect to time of passage past the window and can thus be superimposed on the linear time scale oscilloscope voltage trace. As can be seen from the figure, for a window at mid-stroke, the areas of the piston that pass the window at around the middle of the stroke are effectively squashed, whereas parts that pass the window whilst the piston is reversing are elongated. By contrast, for a window at top dead centre the upper half of the top piston appears stretched.

6. STAGES OF EXPERIMENTAL WORK

The experimental work to be described took place in a series of stages, each one incorporating one or more refinements to the technique. The main stages were

(a) Tests with set-back windows at mid-stroke and TDC using Barnes microscope.

(b) Tests with flush window at TDC using Barnes microscope.

(c) Tests with flush window at TDC using DC-based microscope and computer data acquisition.

Results from the first stage of work were given in the second interim report. This final report therefore concentrates on results from the later two stages, (b) and (c).

7. RESULTS USING A FLUSH-MOUNTED WINDOW AT TOP DEAD CENTRE WITH BARNES MICROSCOPE

Figure 5 shows a whole firing cycle observed through a flush-mounted window at top dead centre with the engine running under zero load. Figure 6 magnifies the region around top dead centre just before and after the engine fires. The lower trace shows a pulse at each TDC position and the centre pulse corresponds to the firing point. On the left in figure 6 the quite cold combustion chamber is observed prior to ignition. The temperature of this chamber can be seen to increase just before the top of the piston moves across the window. This may be due to the gases in the chamber being heated due to compression. From A to B we see the top land followed, from B to C, by the piston ring on its upward journey during the compression stroke. The engine then fires and we see successively the piston ring and the top land (C to D) moving down during the firing stroke. Note that the top land is heating up rapidly. Finally the very hot combustion chamber comes into view. Figures 7 and 8 show similar traces for the engine operating respectively under one third and two thirds of full load.

The oscilloscope traces shown in these figures are voltage values produced, after suitable amplification, by the infrared detector of the microscope. Calibration is needed to convert these to surface temperatures. This is by no means straightforward using the Barnes IR microscope system. There are essentially two problems. One is to determine the emissivity of the observed surfaces and to test that this does not change significantly during a test. The second is that, in the transient AC mode under which these IR voltages were recorded, the actual value of the recorded voltage signal does not dependent directly upon the absolute value of the infrared radiation received but instead is based around a floating average that represents the mean radiation detected. It is necessary to run in the transient mode since this has the fast response needed to follow temperature changes occuring at the speed of the moving piston surfaces. In order to obtain voltage reading that vary directly with temperature it is necessary to use the microscope in "DC" chopped mode where a chopper occludes the signal every millisecond to provide a reference background value.

A two stage calibration was thus required. First the emissivity of each position of the piston ring system was determined by controlling the bulk engine temperature using circulating coolant jacket and rotating the

flywheel by hand, measuring the emitted voltage signal in DC mode. This value was compared to a blackbody source at the same temperature.

To relate AC mode readings to DC mode the engine was run and signals recorded successively in both modes. The DC mode trace could be used in combination with emissivity values to provide reference level temperatures in parts of the cycle where temperature did not vary rapidly - and was steady within the 1ms time limit of the chopped DC mode. These values could then be applied to calibrate the AC trace.

Temperatures calculated in the above manner have been included on figures 5 to 8.

8. RESULTS USING A DC-BASED MICROSCOPE AND COMPUTER DATA ACQUISITION

The technique for obtaining the results obtained in the previous section has two major limitations. One is that the AC nature of the microscope response meant that voltage recorded was not linear with radiance which made calibration cumbersome and inaccurate. In the final stages of the work this was overcome by the construction of a new microscope whose signal processing was carried out in DC-mode.

A second weakness of early work is that the storage oscilloscope employed could only record and average over a maximum of 16 successive traces. Signal averaging over successive engine cycles was found to greatly improve the quality of the temperature trace recorded so it was desirable to average over more than 16 cycles. To accomplish this the oscilloscope was interfaced to a microcomputer so that the latter could read and average signal traces, thereby removing any limits to the number of signals that could be accumulated. In the computer it was also possible to process the radiance data to directly display piston temperature traces.

Oscilloscope traces averaged over 80 successive engine cycles are shown in figures 9 to 11. These show less noise than earlier work, indicating the effectiveness of averaging.

Figures 12 shows temperature traces calculated from the oscilloscope voltage traces in figures 9a, 10a and 11a. The program to calculate these allowed the user to input emissivities for each part of the trace and in figure 12 an emissivity of 1 was used for those parts of the trace where the combustion chamber was in view and the measured value of 0.7 was employed for the piston ring and land regions.

The resolution of the digital storage oscilloscope was only 8 bits or 1 in 256. This meant that the calculated temperature traces in figure 12 have very coarse resolution in the lower temperature range. This is only a limitation when a small oscilloscope voltage scale is chosen so as to accommodate the whole IR signal trace, including the very large combustion peak on the screen. Much more accurate temperature profiles can be obtained for small parts of the stroke by using a larger voltage scale, as shown in figure 13.

9. DISCUSSION

The temperatures measured in both of the stages of work reported above seem to be in reasonable agreement with each other and with previous estimates in the literature. The values obtained with the DC microscope are considered more reliable and are summarised in table 1.

	Chamber	Chamber during comp-ression	Top land	Top ring	Max temp.
No load	126	132	141	138	230
1/3 load	142	150	149	146	290
2/3 load	179	179	175	170	475

Table 1 Temperature Measurements from Diesel Engine °C

Wing and Saunders state in their study (1): "It is generally advised that the metal parts in contact with the piston rings do not exceed 190°C." The current study has measured piston ring surface temperatures at TDC to be between 170 and 200 °C.

From figure 9 to 11 it was possible to estimate the temperature of the

combustion chamber, assuming an emissivity value of unity. At zero engine load this was 250 to 300°C during the firing stroke, rising to 450 to 500°C for full load. Clearly these values are less than the peak temperatures produced during combustion in a diesel engine (approximately 1000 to 2500°C). However it should be noted that the microscope does not see the combustion chamber until approximately 38° of crack angle rotation after TDC, ie after 3.5 ms. Over this time, considerable cooling will have taken place. Very approximate back-extrapolation of the decaying temperature curve observed in figure 11 suggests that the maximum temperature may well have been considerably in excess of 1000°C just after ignition.

Apart from the overall temperature levels reached by the chamber and piston surfaces, the work carried out so far also shows that it is possible to follow the fine details of rapid changes of temperature during a stroke. Figure 14 shows details of the top ring and land area just after firing in one set of tests. At zero and 1/3 load a significant pulse of temperature rise is observed just as the top land comes into view as the piston moves down after ignition. This is swamped by the higher overall temperatures with 2/3 load. This effect may be due to the ingress of a wave of hot combustion gases between the liner and land. It cannot be due to the formation of a higher emissivity deposit at the land/ring junction since this would also cause an proportionate rise in radiance under high load conditions. Some of the results, particularly those at high loads also show a very rapid rise in ring and land surface temperature immediately after firing.

10. CONCLUSIONS

It has been shown that the IR emission method is an effective tool for studying surface temperatures of pistons in an operating engine. The very fast response time ensures that transient effects are observed. Limited results have been obtained so far, with most effort being concentrated upon developing the technique and methodology. However the results show that the temperature of rings, lands and combustion space can be measured with some accuracy and that these, as expected, are very sensitive to engine load. Short duration temperature rises, occuring over less than a millisecond, have also been observed on the piston land just after firing.

11. EXTENT TO WHICH ORIGINAL OBJECTIVES HAVE BEEN MET

Objectives Met

1. Set-back and flush-mounted sapphire windows have been succesfully mounted in a Petter engine in such a way that they can withstand engine firing conditions for reasonable test times.

2. A procedure, including a scope triggering system, signal delay method and an infrared microscope attached to an oscilloscope/microcomputer set up has been devised able to capture and average infrared radiance traces from a firing engine with a time resolution of less than $50\mu m$.

3. Infrared radiance traces have been obtained from the combustion chamber and the moving piston surface of a firing diesel engine.

4. Calibration has been carried out to convert radiance traces to temperature traces.

5. A modified form of IR microscope has been built able to operate at high speed in DC mode.

6. Combustion chamber, piston rings and piston land temperatures have thereby been obtained from a firing Petter AV1 diesel engine operating at three load levels.

Objectives not met

Two components of the originally proposed work have not yet been accomplished. One is the development of a duel wavelength technique. The aim of this was to measure IR radiance at two different wavelengths which would overcome the need to measure in a separate calibration emissivity of the surfaces involved. A system has been designed for this and is shown in appendix 1. However delays in delivery and other equipment problems meant that it was not possible to test this within the time available.

The second component of the work which could not be accomplished in the time available was to use a diamond window and test the practicability of using optical interferometry to determine film thickness in piston rings. This is still considered a feasible approach but was not possible in the time available. It was accorded lower priority than temperature measurement in view development of the fluorescence film thickness method (11).

12. LIST OF PUBLICATIONS ON WORK CARRIED OUT

1. The first two stages of the work were presented at Leeds/Lyon Conference on Automotive Engineering at Leeds in September 1990. The paper will appear in the proceedings of this Conference, published by Elsevier, in 1991.

2. A brief summary of the work will be presented as a poster at the I.Mech.E. Conference on Infrared Combustion Engine Research in January 1991 in London.

3. A paper will be submitted on the completed work for presentation at the annual STLE/ASME meeting in St Louis in October 1991.

REFERENCES

1. Wing, R.D. and Saunders Sir Owen. "Oil Film Temperature and Thickness Measurements on the Piston Rings of a Diesel Engine." Proc I.Mech.E. 186 pp 1-9 (1972).

2. Whitehouse, N.D. Annard, W.J.D. and Ma, J.H. "Heat Transfer in Compression Ignition Engines." Proc.I.Mech. E. 185 pp 963-987 (1970-71).

3. Furuhama, S. and Suzuki, H. "Temperature Distribution of Piston Rings and Piston in High Speed Diesel Engine." Bull. JSME 22 pp 1788-1795 (1979).

4. Ip. E.S. "Temperature Distribution in Diesel Engine Pistons." The Engineer 214 pp 935 (1962).

5. Fitzgeorge, D. and Pope, J.A. "An Investigation of the Factors Contributing to the Failure of Diesel Engines Pistons and Cylinder Covers." Trans N.E. Coast Inst Engrs and Shipbuilders 71 pp 163 (1955).

6. Ivanou Yu, M., Kovalenko, V.A., Morozov, V.A., Nekharoshev, S.A., Nikokenko, V.A. and Potichenko, V.A. "Temperature Measurement of Piston Parts in a High-Speed Two-Stoke Engine by Means of a Crystalline Temperature Meter." Probl. Prochn. 2 pp 45-46 (1986).

7. Jaeger, J.C. "Moving Sources of Heat and the Temperature at Sliding Contacts." Proc Roy Soc NSW 56 pp 203-214 (1942).

8. Pywell, R.F. and Pike, W.C. "The Effect of Lubricants on Piston Ring Scuffing: Part 1 - Development of an Engine Test." Inst. Pet. Symp. Montreux, 2-6 April 1973.

9. Crooks, T. "The Effect of Additives on Piston Ring Scuffing." DIC Thesis, Imperial College, London, August 1975.

10. Jeffs P.T. and Macpherson, P.B. "Infra-Red Surface Temperature Measurements of Lubricated Contacts in Laboratory Test Machines." Final Report to MOD Contract K/A12/1122, MTL 3, Jan 1979.

11. Hoult, D.P., Lux, J.P. and Wong V.W. "Calibration of Laser Fluorescence Measurements of Lubricant Film Thickness in Engines." SAE 881587.

12. Lux, J.P. and Hoult, D.P. "Lubricant Film Thickness Measurements in a Diesel Engine Piston Ring Zone." STLE Preprint 90-AM-1H-1. (1990).

APPENDIX 1

A schematic diagram of the proposed dual wavelength system is shown below. A sapphire pyrometer rod will be embedded in the cylinder wall to replace the sapphire window currently in use, this will give a more efficient transfer of radiant energy from the contact zone to the IR detector. It will also remove any spurious IR contributions from the laboratory environment. Radiance measurements will be made at two discrete wavelengths determined by two narrow band IR filters that are mounted on a moveable slide within the optical path. This will allow measurements to be made concurrently at each wavelength and the ratioed result and hence temperature determined.
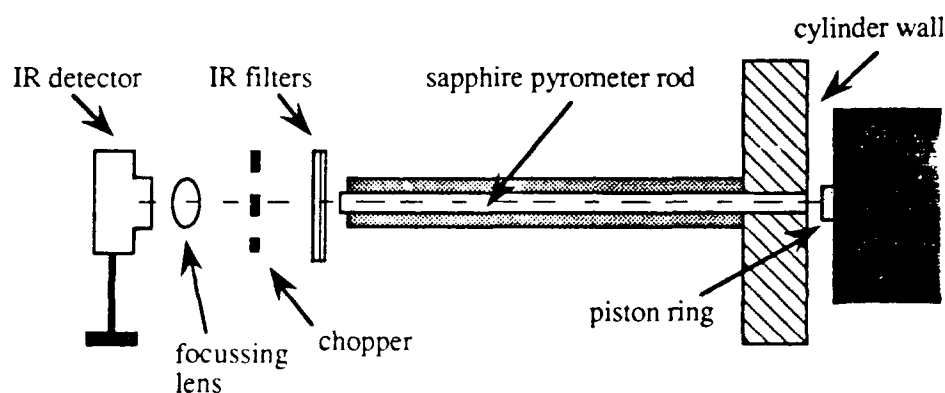
Proposed dual wavelength system
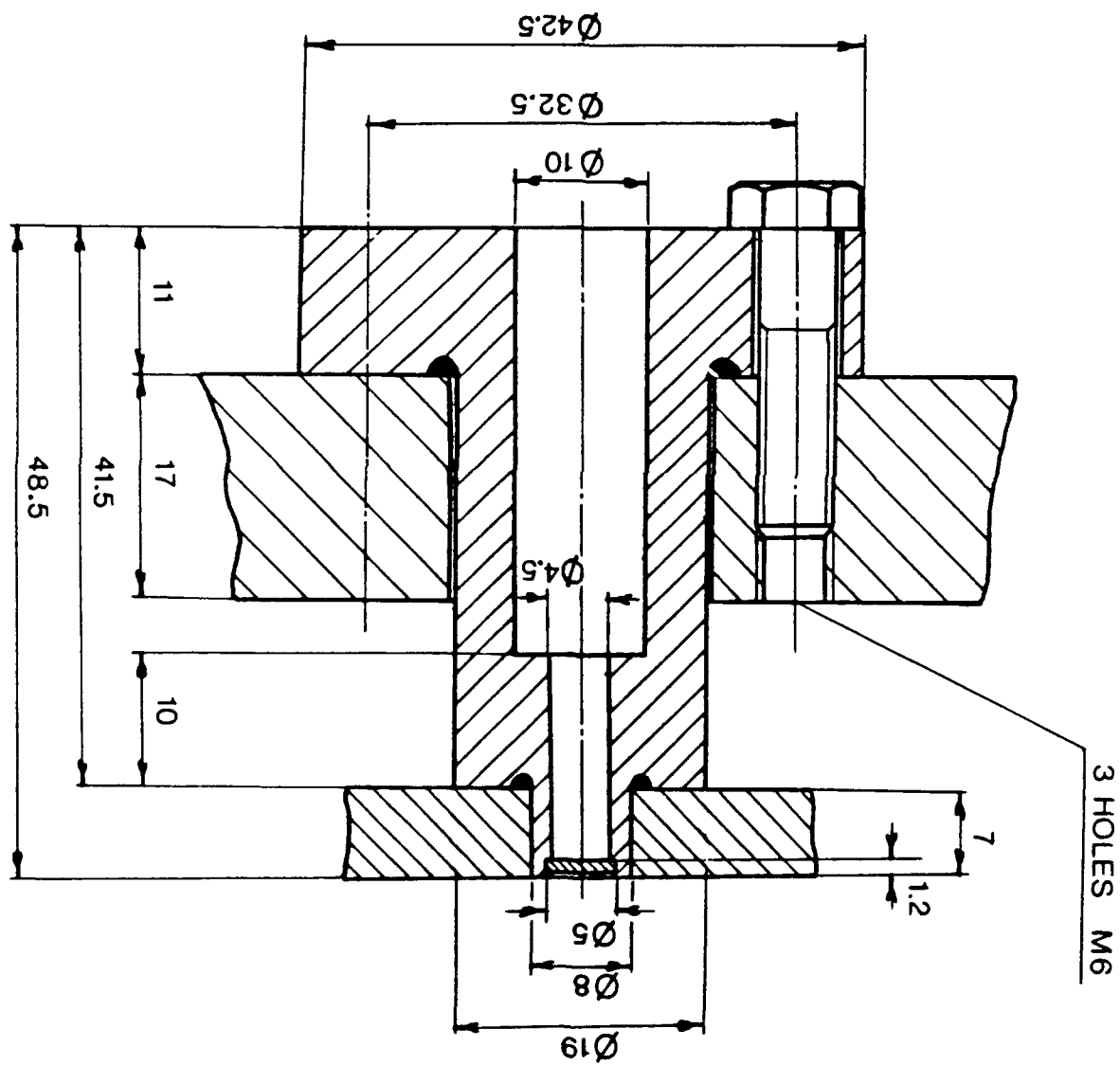
Figure 1.   Window Design
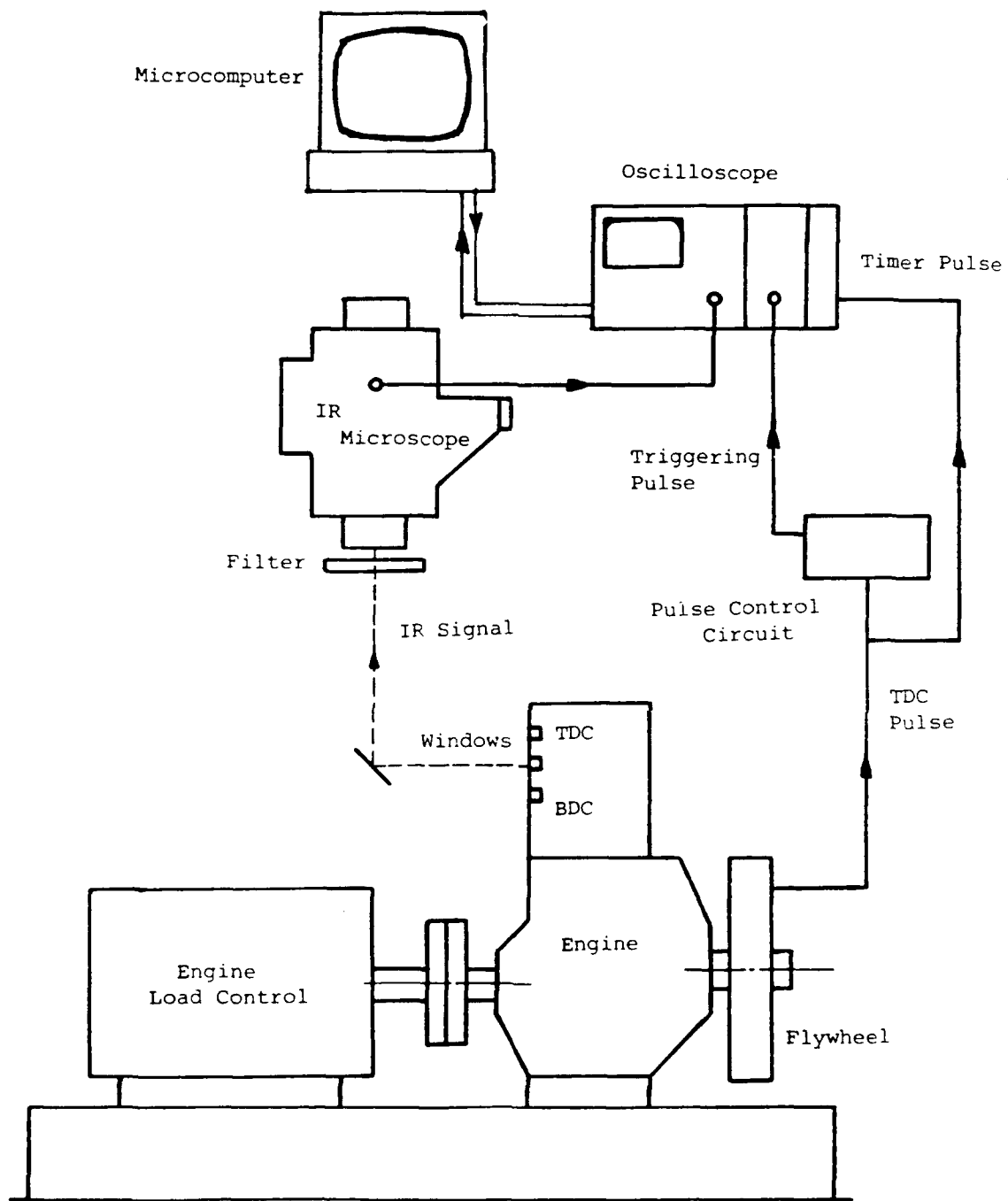
Figure 2. Schematic Diagram of Test Set Up
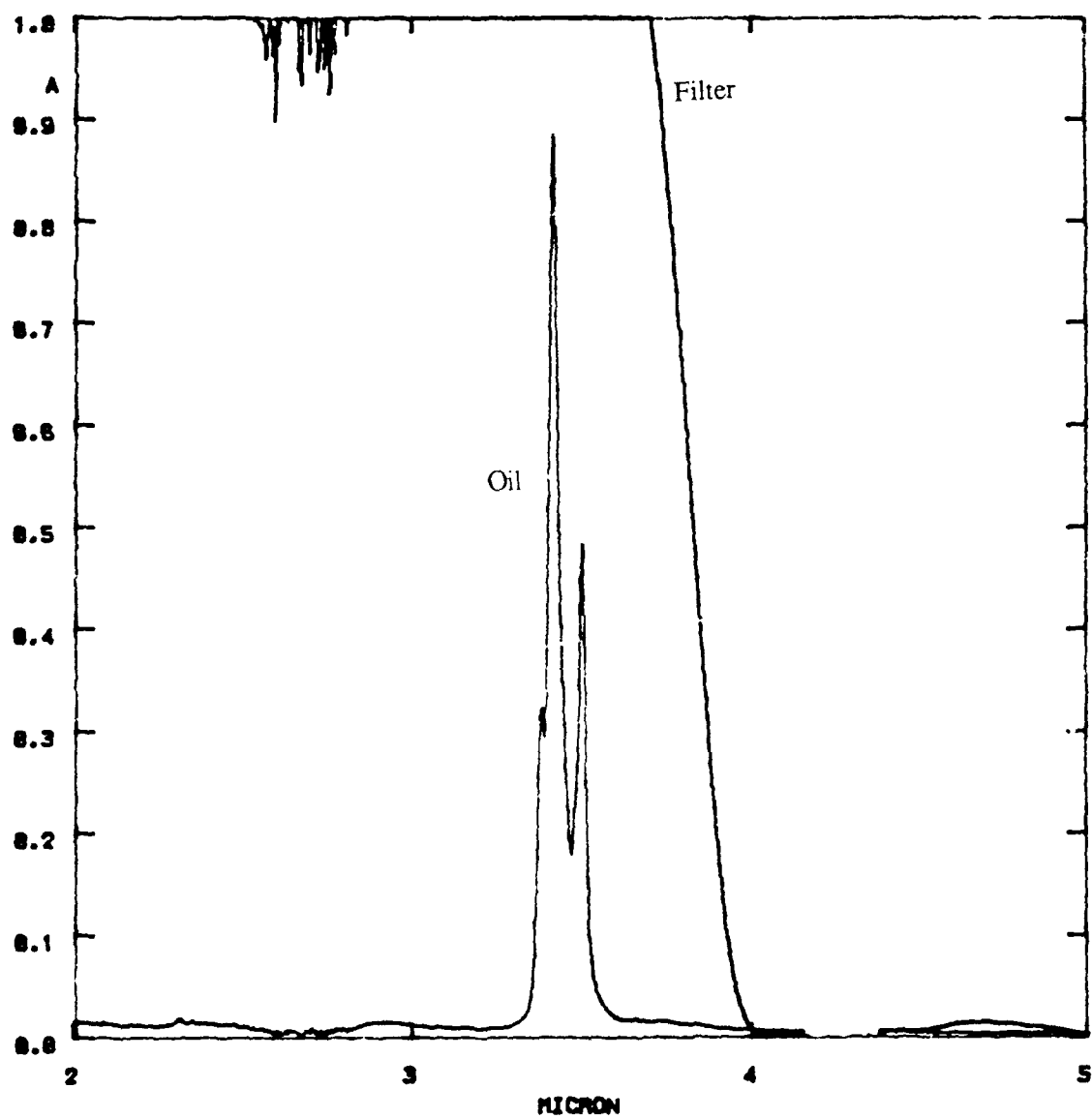
Figure 3. IR Absorbance Characteristics of Filter

(a) Actual Piston Shape
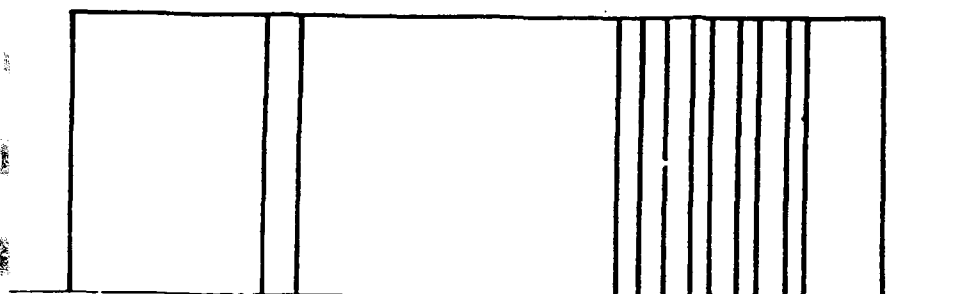
(b) Perceived Piston Shape

TDC

BDC

(i) Through
window at
BDC

(ii) Through
window at
mid-stroke

(iii) Through
window at
TDC
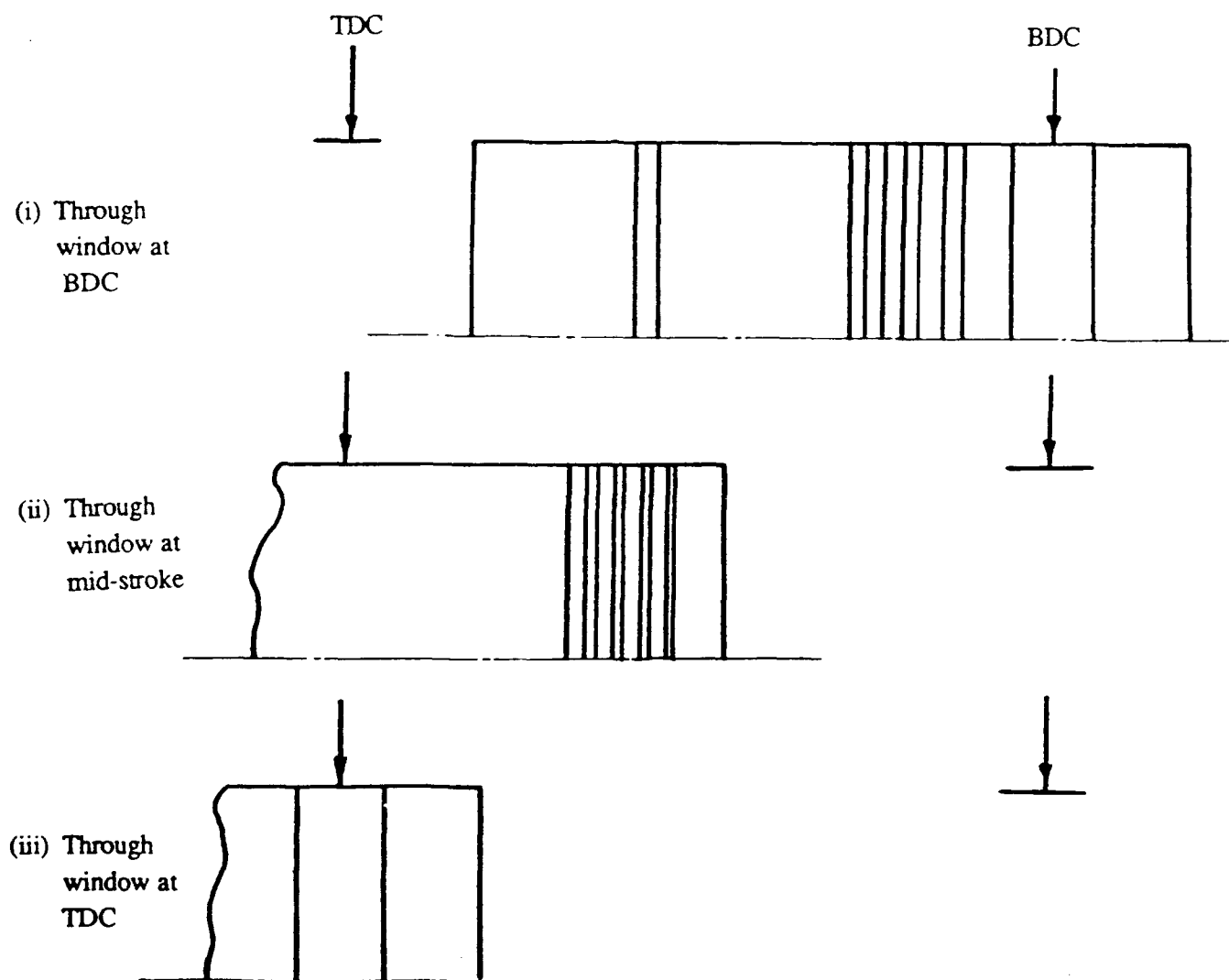
Figure 4. Influence of Motion on Apparent Piston Shape
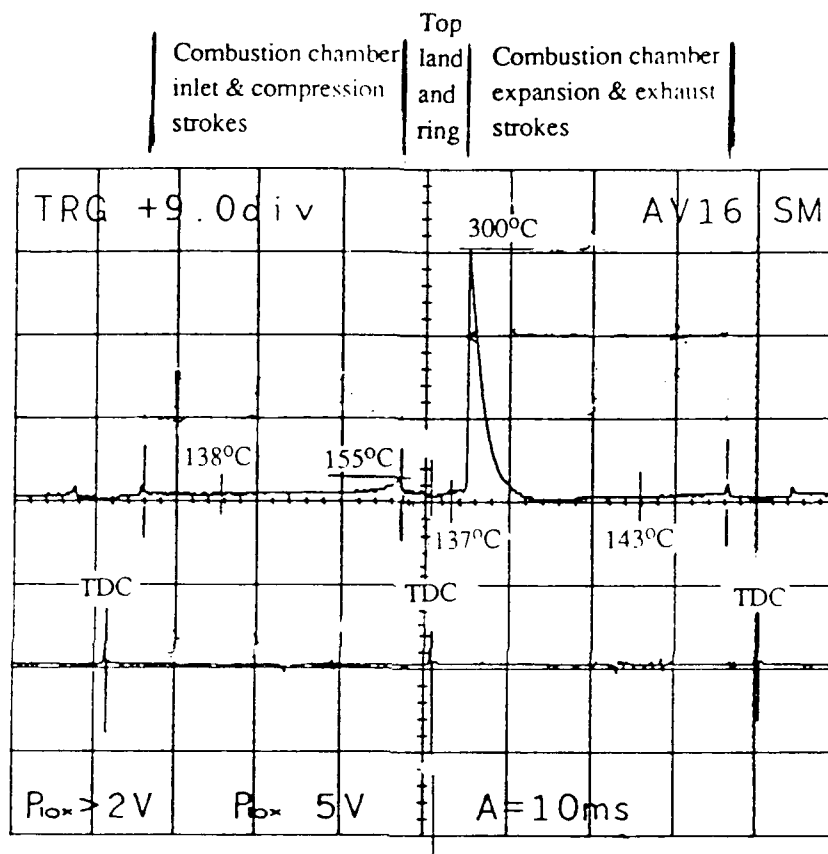
Figure 5. Trace from Flush Window at TDC. No Load.
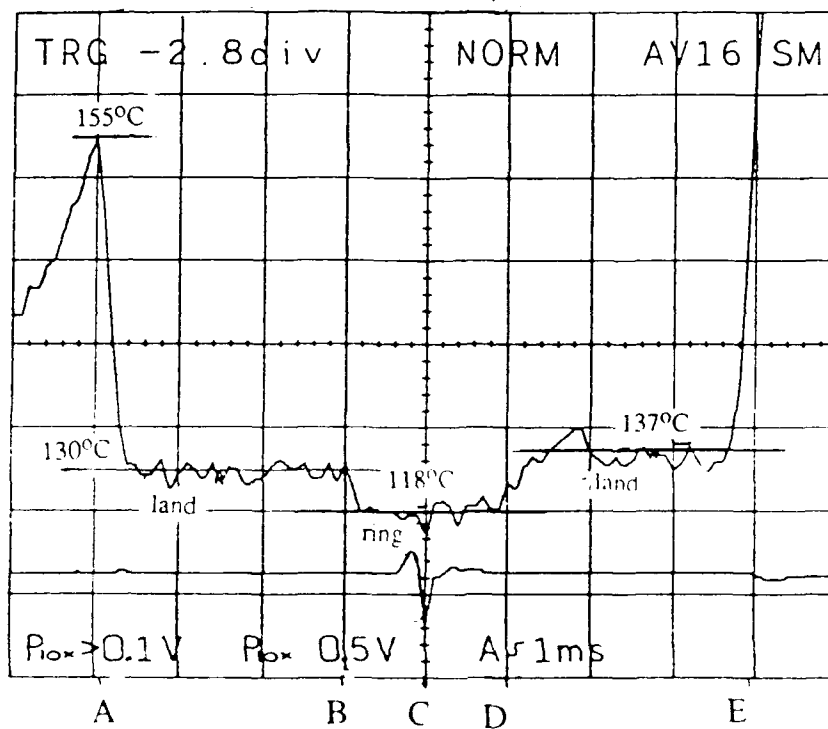
Figure 6. Just Before and After Combustion. (No Load).
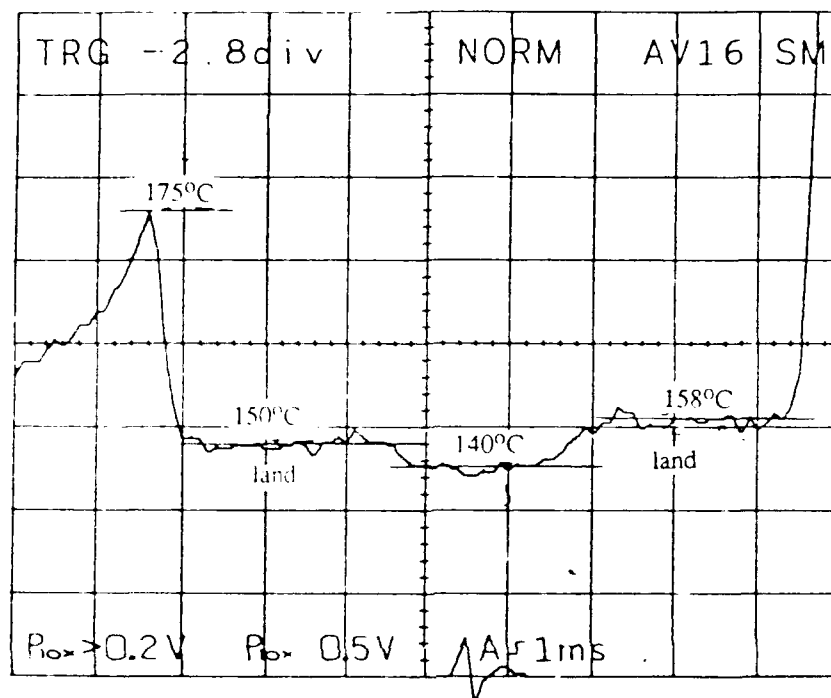
Figure 7. Just Before and After Combustion
(One Third of Maximum Load)
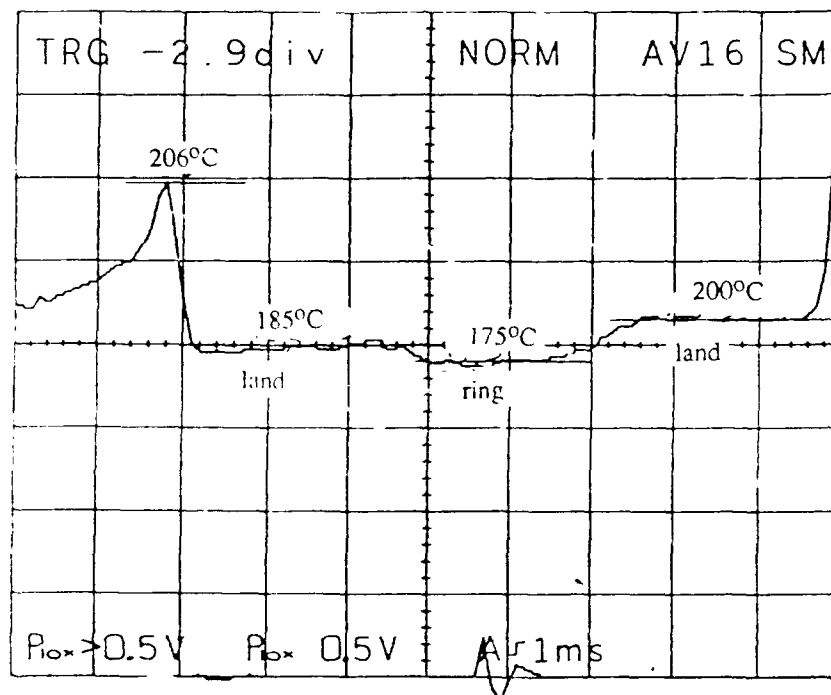
Figure 7. Just Before and After Combustion.
(Two Thirds of Maximum Load).
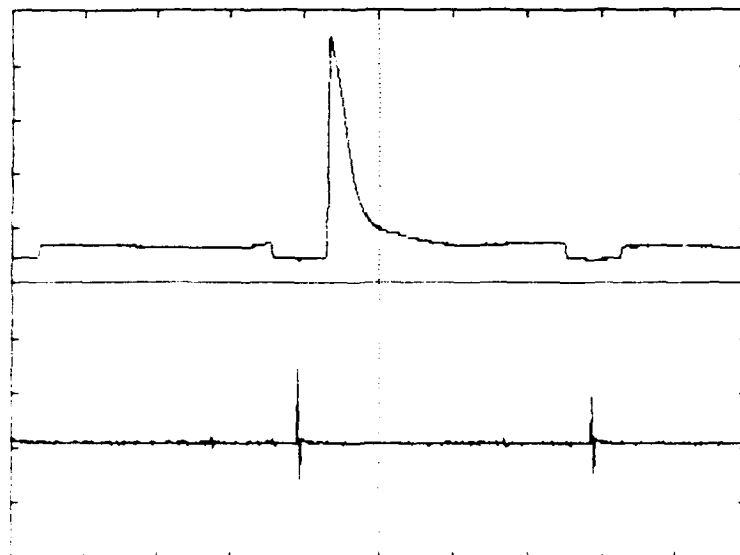
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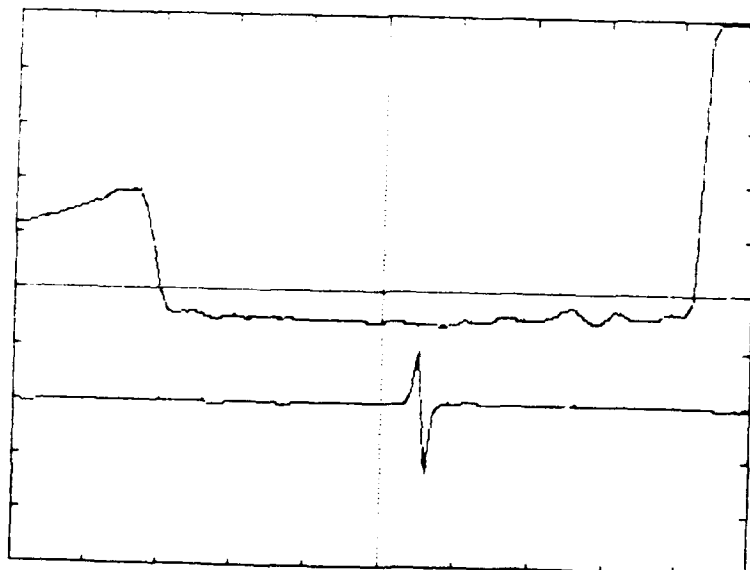
(b)   Detail Around Ignition

Figure 10.   Radiance Trace Under $^1/_3$ Load
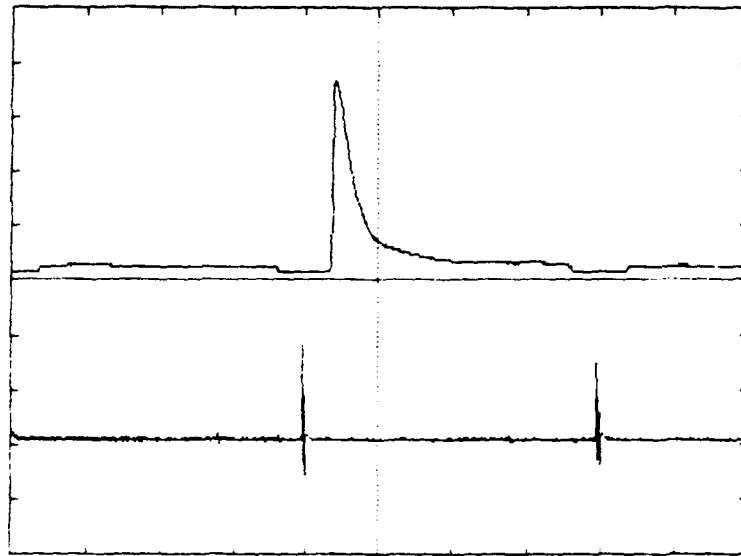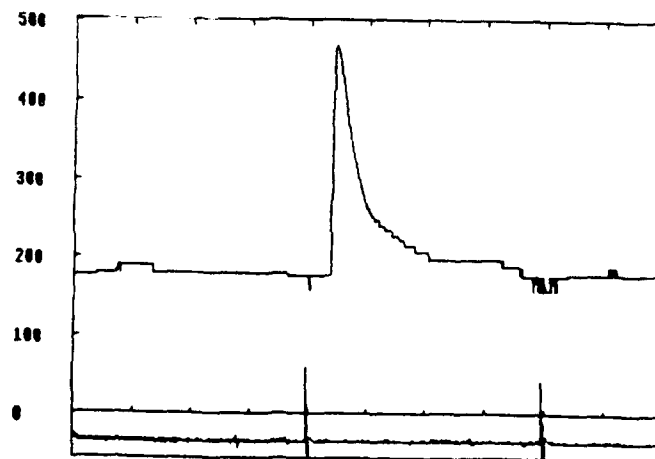
(a)   Full Engine Cycle
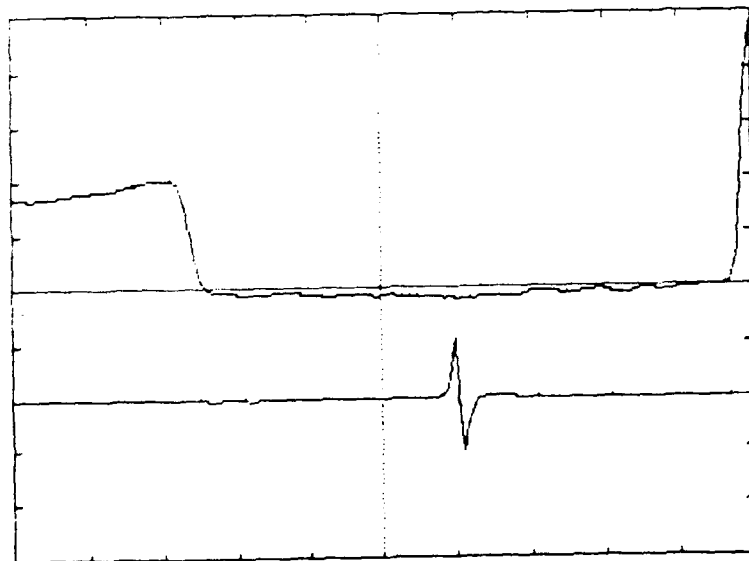
(b)   Detail Around Ignition

Figure 11.   Radiance Trace Under $^2/_3$ Load

(a)   Full Engine Cycle
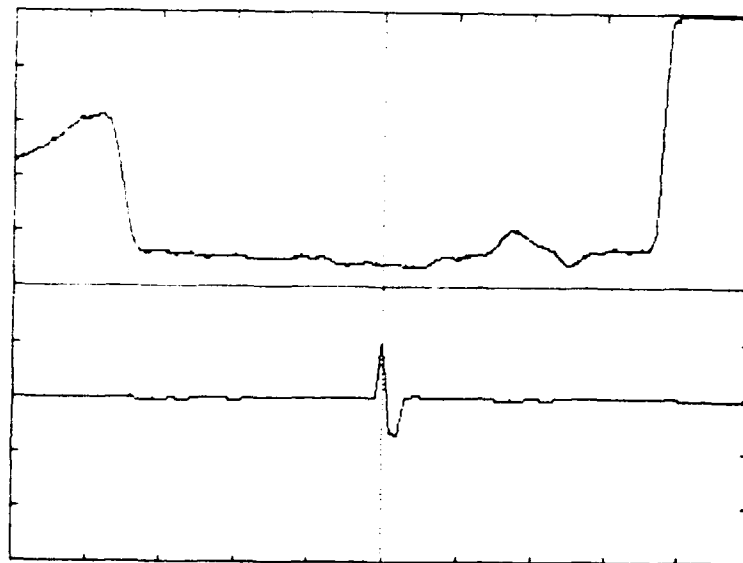
(b)   Detail Around Ignition

Figure 9.   Radiance Trace Under Zero Load

(a)   Zero Load

(b) $^{1}/_{3}$ Load

(c) $^{2}/_{3}$ Load
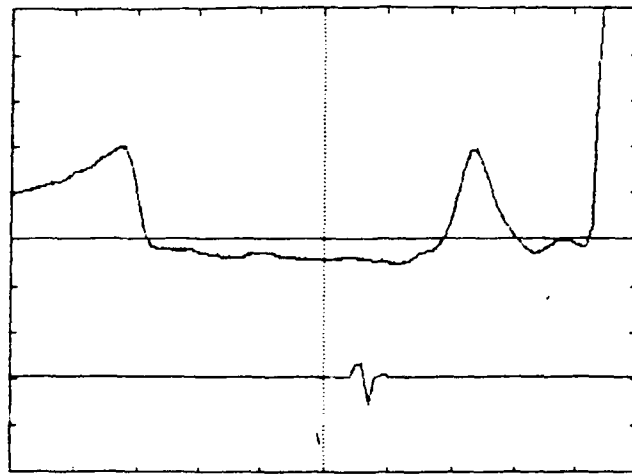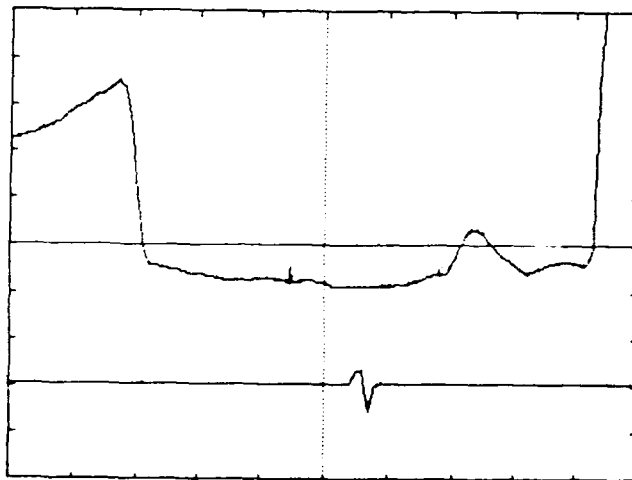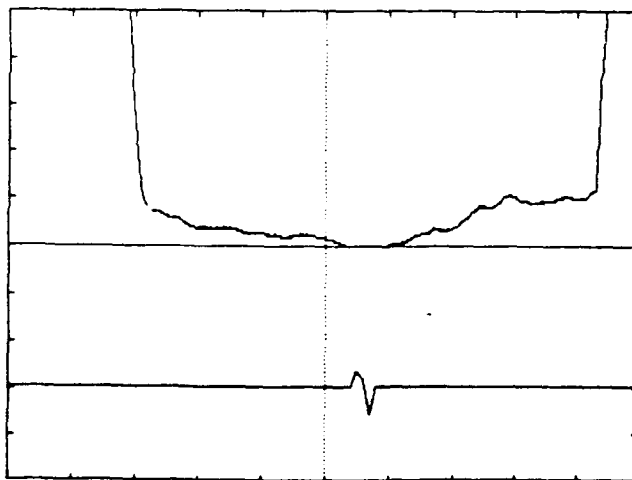
Figure 12.   Temperature Curves From Radiance Traces
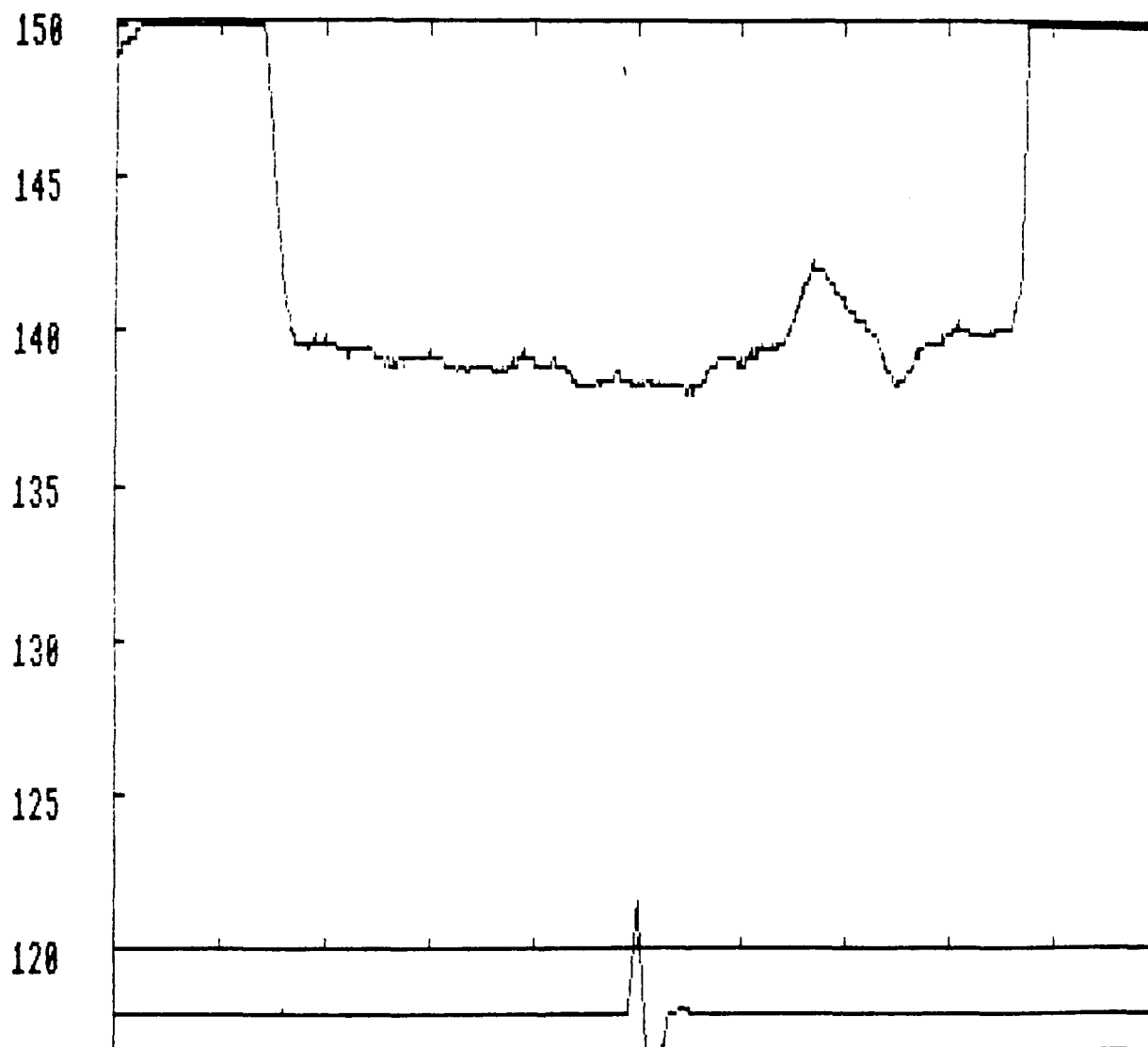
Figure 13. Details of Temperature Curve Around Ignition
For Zero Load

(a) Zero Load

(b) $^1/_3$ Load

(c) $^2/_3$ Load

Figure 14. Details of Radiance Traces Around Ignition